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Optimum design and layout of the cooling apparatus for long compaignship blast furnace

Shusen Cheng[1], *Tianjun Yang*[1], *Qingguo Xue*[1], *Haibin Zuo*[1], *Xiaowu Gao*[2], *and Weiguo Yang*[2]

1) Metallurgical Engineering School, University of Science and Technology Beijing, Beijing 100083, China

2) Ironmaking Department, Beijing Central Engineering and Research Incorporation of Iron and Steel Industry, Beijing 100053, China

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Abstract: Generally, the cooler life can determine the blast furnace life. The slag-metal skull frozen on the cooler can separate the cooler from the hot gas flow in blast furnace. The key problem is how to freeze liquid slag-metal on the cooler, and the main measure is to decrease the hot surface temperature of the cooler. The computational technology of heat transfer was practically used for long campaign blast furnace design. The optimum design of the cast iron stave, copper stave, plate-stave combined system and flange stave was given by the computing results. According to the results, the optimum arrangement of different coolers (cast iron or copper stave, flange stave and plate-stave combined system) on different height of blast furnace wall can be found through all these temperature fields.

Key words: blast furnace; cooler; optimum layout; computational

1 Introduction

Now the most easily damaged part of a common designed blast furnace is the blast furnace wall of lower shaft because any refractory lining can not stand the erosion of liquid slag and hot metal for long time under high temperature. But it should be known that, as the refractory lining is worn out, it does not mean the worn-out of the furnace. The campaign life of blast furnace is not determined by the refractory lining itself but by the cooling apparatus. If the cooling apparatus can be properly designed, the liquid slag and hot metal can be frozen on its hot surface. There will be a new blast furnace wall composed by cooling apparatus and solidified slag. If the cooling apparatus is all right, the frozen slag can be worn out today but tomorrow it can establish a new solid slag-metal layer again on the hot surface of stave in endless cycles, or say the blast furnace wall can stand for long time.

At present, there are so many blast furnaces of smelting ferromanganese without lining, their refractory lining is actually replaced by the frozen slag-metal layer. It is sure that there is temperature fluctuation on the wall, the slag lining can be melted down, but the cooling apparatus can freeze the liquid slag again in short time. The authors believe that the campaign life of lower shaft (the working area with liquid slag) is not determined by its lining but by the cooling apparatus. From point view of theory of heat transfer, the cooling apparatus of blast furnace can be designed to make its hot surface temperature be less than its burn-out temperature [1-6].

2 Model for cooling apparatus

2.1 The physical model

In our country the main cooling apparatus are of common stave and flange stave, plate-stave combined system and copper stave. Their physical models can be found in references [1-4].

2.2 The mathematical model

The 3-dimensional heat transfer differential equation:

$$\nabla(\lambda(T)\ \mathrm{grad}T(x, y, z)) = 0 \quad (1)$$

where λ is the heat transfer coefficient, W/ (m·℃); T, the temperature, ℃; x, y, z, the space coordinates, respectively.

The definitive conditions for the solution is as follows.

(1) The secondary boundary condition [1-4] on the symmetrical surface, in general, the heat flux is assumed to be zero;

The heat transfer between furnace shell and environment is convection of thirdly boundary condition;

$$\alpha = 9.3 + 0.058\ T_W \quad (2)$$

where T_W is the surface temperature of the furnace shell, ℃; α, the synthetic convection heat transfer co-

Corresponding author: Susen Cheng, **E-mail:** chengsusen@metall.ustb.edu.cn

efficient, W/ (m^2·℃).

(2) The heat transfer between cooling plate and cooling water is convection, namely, the third boundary condition, according to Titus-Boelt formula, the heat transfer coefficient is

$$k = (\lambda/d)\, Nu \qquad (3)$$

$$Nu = 0.023 Re^{0.8} Pr^{0.4},$$

where k is the convection heat transfer coefficient between cooling water and cooling plate, W/ (m^2·℃); d, the equivalent diameter of the cooling channels of cooling plate, m.

(3) The synthetic convection heat transfer coefficient (h) between the cooling equipment and the cooling water is

$$h = 208 + 47.5\, V \qquad (4)$$

where V is the water rate inside the water pipe of the cooling equipment, m/s.

(4) The boundary condition between the furnace lining and the gas is assumed as heat transfer by convection, the heat transfer coefficient is considered as:

$$h_1 = 232\ (\mathrm{W/m^2.℃}) \qquad (5)$$

The gas temperature in the furnace is assumed as 1200℃.

3 Analysis of calculation results

3.1 Flange stave

In the past, flange staves (iron cast) were used on the medium and lower part of blast furnace shaft, or say to the wet area. The function of flange on the stave is as lever beam for supporting refractory lining and slag-metal skull, at the same time, the flange is also good for protecting the flange from overheating. But in practice, the common designed flange stave can stand only less than 2-3 years. The refractory lining is also damaged because of losing their supporters. We hope to reduce the hot surface temperature through changing the structure of flange stave.

Figure 1 shows the change of the temperature field as the distance (d) between the designed cooling pipe and the hot surface decreases from 250 to 210 mm or increase the water velocity (V_w), but finally the temperature of the hot surface still keeps higher than 760 ℃ (the safety temperature limit of cast iron) [4]. The burnout of flange is difficult to be eliminated. **Figure 2** shows that as the blast furnace gas temperature lowers down to 900℃, the situation becomes much better.

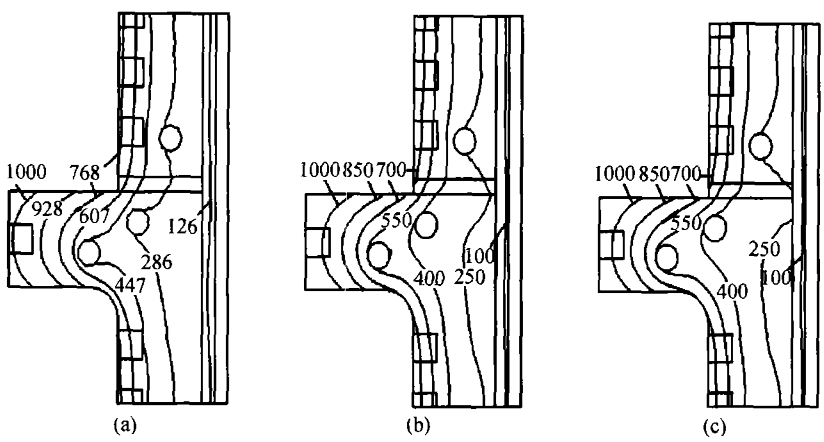

Figure 1 The temperature distribution in blast furnace wall *vs.* cooling intensity (T_f = 1200℃), (a) d=250 mm; (b) d=210 mm; (c) V_w=2.5 m/s.

Even the flanges are exposed to the hot gas flow, their hot surface temperature is still less than 760℃ and also a layer of brick lining can be kept, because its temperature is not more than 870℃. From these two figures, the modified design doesn't give a satisfied result on decreasing the hot surface temperature (less than 760℃) of the flange. It shows that the flange staves are suitable for the upper part (dry area) of the shaft but not the lower part (wet area).

3.2 Plate and stave combined system

The flange stave is not used on the lower part of the shaft, so the plate-stave combined system is brought forward. The special feature of this system is that the cooling plate works as a supporter of the brick lining which protects the stave itself from overheating. According to the computational results for the flange stave, it is thought that the cooling plate should be made by using the material with higher conductivity. The copper conductivity is ten times bigger than that of iron cast and copper has good mechanical performance, therefore, copper is chosen as the material to make the cooling plate. In order to sustain the mechanical strength, the maximum temperature of the tip of copper plate should not be higher than 230℃. **Figures 3** and **4** show the temperature distribution in blast furnace wall with plate-stave combined system. The thickness of the remaining brick lining is the same as that of the plate extension. The thickness of the remaining brick lining is 190, 95, 47.5 mm, respectively. Figures 3 and 4 tell us that the thicker the remaining brick lining is, the higher the temperature within the remaining brick lining will be. As the thickness of the remaining brick lining is more than 95 mm, the hot surface temperature of the brick lining is higher than 870℃ (the critical temperature of destruction of the cast iron stave), it is difficult for the brick lining to stand this temperature. But in the case of very thin remaining brick lining ((c) 47.5 mm), the plate is with shorter extension time, the temperature within the remaining lining can be lowered down to 870℃ or less. As the gas temperature increases to 1500℃ (figure 4), the temperature within a thinner brick lining can still keep below 870℃, it shows that the plate and stave combined system can be applied to the lower part of the blast furnace shaft, and even to the belly part. Figures 3 and 4 make a negative answer on the topic "the longer plate extension time keeps the thicker remaining lining." Actually the thicker the brick lining is, the easier it is burnout. After the brick lining is burn out, it is also dangerous as the tip of the longer plate extends into the hot gas stream. Furthermore, as the extended plate tip is inserting into the hot gas stream, the blast furnace inner wall will not become smooth, it is harmful for blast furnace to run smoothly, the thick brick lining will also waste refractory and increase construction cost.

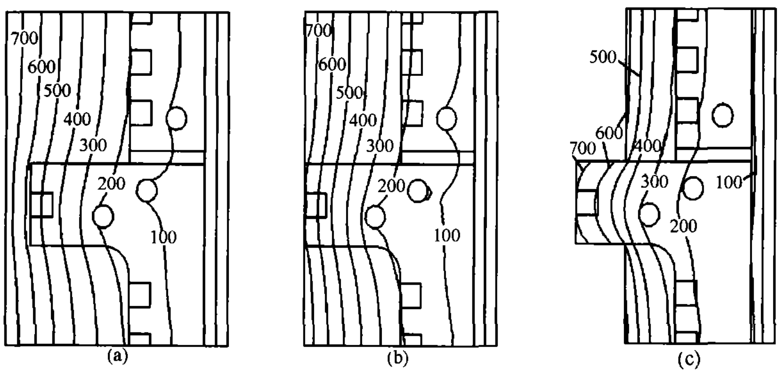

Figure 2 The temperature distribution in blast furnace wall *vs.* the thickness of brick lining (d_b) (T_f = 900℃), (a) d_b=425; (b) d_b=340; (c) d_b=170 mm.

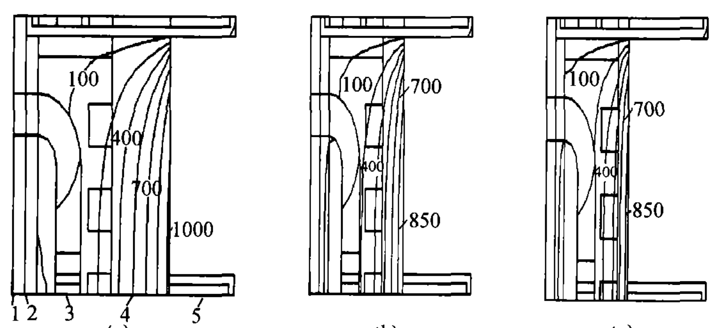

Figure 3 The temperature distribution in blast furnace *vs.* the thickness of brick lining (d_b) (T_f =1300 °C), 1—shell; 2—filling; 3—stave; 4—brick; 5—cooling plate; (a) d_b=190; (b) d_b=95; (c) d_b=47.5 mm.

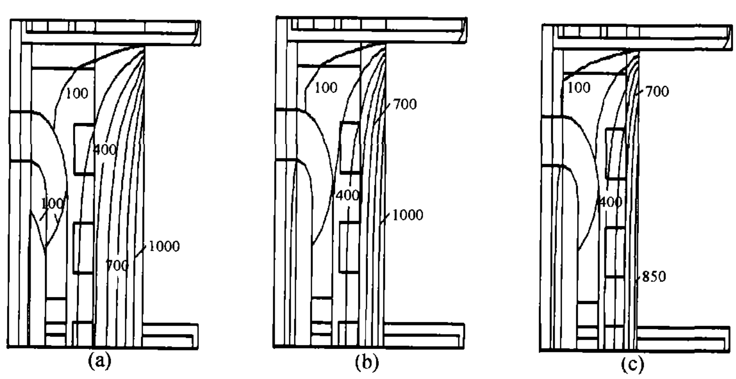

Figure 4 The temperature distribution in blast furnace *vs.* the thickness of brick lining (d_b) (T_f = 1500 °C), (a) d_b=190; (b) d_b=95; (c) d_b=47.5 mm.

3.3 Copper stave

Copper stave posses very well thermal property in our calculation. **Figure 5** shows the influence of the blast furnace gas temperature on the hot surface temperature and the heat flux of a bare copper stave. It can be seen that as the heat flux is high up to 240 kW/m^2, the temperature of the copper stave proper is not over 200℃. The temperature is so low that the liquid slag is easier to be stuck on the hot surface as a skull for protecting the stave itself.

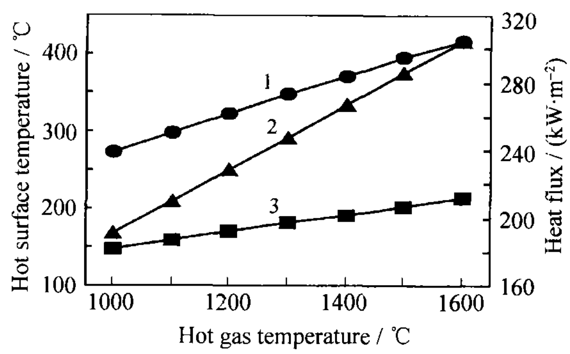

Figure 5 The influence of blast furnace gas temperature on hot surface temperature and heat flux, 1—hot surface temperature of brick lining; 2—heat flux into stave; 3—hot surface temperature of rib.

Because of a drilling hole in copper stave instead of casting steel pipe in cast iron stave, the heat resistance of the coating cooling water passage and the clearance resistance between the cast iron and the cooling water passage is eliminated. From this point not only the temperature difference inside the stave proper decreases but also the high thermal tension decreases. It is not necessary to worry about the high heat loss through blast furnace wall with the high thermal conductivity of copper stave because the higher conductivity is, the thicker the slag skull can be formed. The heat loss can be reduced to a certain level and the slag skull has very good effect on protecting the copper stave from overheating. **Figure 6** shows that there is a 10 mm slag skull on the hot surface of the copper stave (the common working case), and the working condition is very good for the blast furnace wall (low heat loss) and much more safety for the copper stave. Comparing figure 5 with figure 6, it can be seen that a 10 mm thickness of slag skull on the hot surface of copper stave can make the rib of the copper stave be lowered down to 100℃ or so. As the gas temperature increases from 1000℃ to 1600℃, the highest temperature of the rib can be kept as a constant, not more than 100℃ or so, the heat flux through blast furnace wall lowers down to one third of the heat flux of the copper stave without the slag-metal skull. From all these calculations, the authors would like to put stress on the following two points. Firstly, the heat resistance of copper stave is one tenth of that of cast iron stave, so the water scale within the cooling water passage has more important effect on copper stave than that on cast iron stave, so if the blast furnace wall uses copper stave as its cooler, the scale-free cooling water is absolutely necessary. For instance, 3 mm water scale on the cooling water passage will make the temperature of copper rib surpass its limit temperature of destruction. Secondly, although the heat resistance of the copper stave is only one tenth of that of the cast iron stave, the heat loss is not ten times as that of the cast iron stave. The heat loss of the blast furnace wall using the two kinds of staves is rather close.

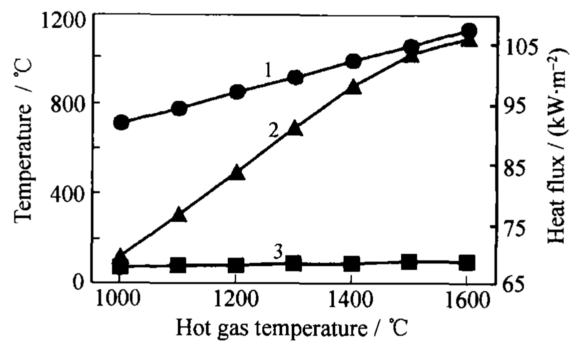

Figure 6 The influence of blast furnace gas temperature on hot surface temperature and heat flux, 1—maximum temperature of stave hot stave; 2—heat flux into stave proper; 3—maximum temperature of rib.

Figure 7 [7] shows that the yield and tensile strength of copper changes with its temperature, as the temperature increases, the strength decreases sharply. The figure also shows that it is rather dangerous as a bare copper stave is exposed in blast furnace hot gas for a long time. In common case the hot surface is about 100℃, so the liquid slag is easier to be stuck on its surface. The slag will freeze a protecting layer for copper stave. From this point of view, the copper stave is suitable for using on the wet area of blast furnace. In a word, in order to prolong the copper stave life, the hot surface of copper stave must be solidified a layer of slag skull. Now the blast furnaces in China are not running very well for the unreasonable design and installment of coolers.

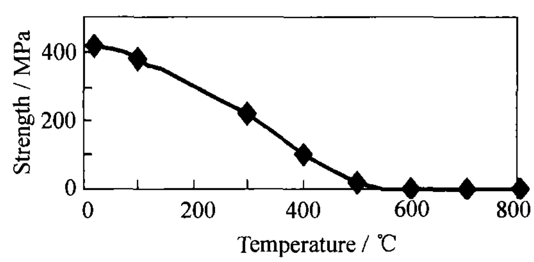

Figure 7 The change of mechanical strength *vs.* temperature.

3.4 Conventional cast iron staves

When the hot gas temperature is 1200℃, the following calculating results were obtained. **Table 1** shows that the hot surface temperature might be more than 760℃ when the cast iron stave is without slag skull. The stable slag skull is a key for the cast iron stave of long campaign life, therefore conventional cast iron stave is suitable for the upper and middle part of the shaft. In order to freeze slag-metal skull on the cast iron stave, it should be with larger diameter pipe (ϕ70-80 mm), shorter distance between two pipes, straight cooling pipe and hot surface of stave (≤200 mm), thinner inlaid refractory layer (30-65 mm). The structural parameters and computational results of different designed cast iron staves are listed in table 1. It is evident that the two kinds of improved design staves can satisfy the requirement of overheating-free. It shows that the maximum temperature and heat flow is lowered down.

Table 1 Improvements on cooling stave design

Item	Prototype	1th improvement	2nd improvement
Total thickness of stave / mm	260	260	240
Diameter of cooling pipe / mm	70	80	80
Distance between the centerlines of cooling pipes / mm	254	200	180
Distance between centerline of cooling pipe and hot surface of stave / mm	160	140	140
Thickness of inlaid brick / mm	75	75	55
Surface area of cooling pipes / hot surface area	0.865	1.256	1.396
Limit temperature on hot surface (bare stave, no lining) /℃	864	804	761
Limit heat flow on hot surface (bare stave, no lining) / ($kW \cdot m^{-2}$)	74	87	97
Maximum temperature on hot surface with 10 mm slag skull /℃	572	503	458
Maximum heat flux on hot surface with 10 mm slag skull / ($W \cdot m^{-2}$)	49	54	58

4 Conclusions

(1) The modified design for the flange stave does not give a satisfied result on decreasing the hot surface temperature (less than 760℃) of the flange when the gas temperature near blast furnace wall is 1200℃, so the flange stave is suitable for the upper part (dry area) of the shaft but not the lower part (wet area).

(2) The shorter the protruding length of the cooling plate is, the lower the hot surface temperature of the brick lining between two plates is. The plate and stave combined system can be used on the lower part of the blast furnace shaft, and even in the belly part.

(3) The high conductivity of copper can guarantee that the hot surface temperature of the copper stave is so low that the slag-metal skull can freeze on the hot surface of the copper stave. The heat loss can be reduced to a certain level and the slag skull has very good effect on protecting the copper stave from overheating. The copper stave is good for wet area.

(4) The cast iron stave can be installed on the upper part of wet area through the optimum design of the conventional cast iron stave.

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